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Title of the paper:
A geo-archaeological approach to the study of hydro-agricultural systems in arid areas of Western Syria

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Abstract
Over the last 30 years, geoarchaeological surveys undertaken in the Near East have offered a powerful way of studying, *inter alia*, water supply systems at a microregional to regional scale. However, efforts to synthesize the results of surveys at a sub-continental scale in order to understand local differences and similarities, and compare local strategies through time, require specific tools. In this paper, we develop a methodology designed to characterize and facilitate comparison of strategies employed across the arid areas of Western Syria. This requires microregional field studies undertaken at the level of specific landscapes to be integrated within a wider GIS framework, based upon thematic layers (soils, rainfalls, hydrology) at a uniform spatial scale of assessment (in this case the pixel of a Landsat image), and a common description of the agronomic potential in those areas in which specific hydraulic installations were employed. In contrast to the usual practice of modelling, which depends upon the downscaling of environmental data (land cover, rainfall maps) generated at a continental scale, we stress here the need to generalize upwards, from observations made at the microregional level, by using common descriptors and qualitative indicators. The GIS analysis of these data provides a weighted average model derived from field evidence for the different technical choices made (i.e. the decision to utilize specific water management devices) in relation to the various agronomic landscapes.

Keywords: Syria, geoarchaeology, aridity, water management systems, GIS-based spatial analysis, land use models

1. Introduction

An account of the long-term history of landscape change is of great importance for understanding the complex interaction between climatic change (both slow variation or abrupt events), human activity and impact and historical interpretations of social and political developments. Archaeologists, historians and climate specialists have devoted a great deal of attention to the connection between societal changes and environmental crises or abrupt events (Weiss et al., 1993; Kaniewski et al., 2008; Weiss, 2012). However, far less attention has been accorded to modelling long term landscape history.
Human-environment interactions can be broadly framed as either local-scale adaptation to given affordances, or as the development by human groups of devices which allow the exploitation of new resources, and may therefore induce changes in the landscape. From this standpoint, hydro-agricultural systems provide a good case study for understanding the history

of human activity in arid areas, because they are often better understood as developments specific to particular local regions, than as systems developed on a common basis across large geographical extents.

More than a dozen separate archaeological/environmental surveys have been carried out in western Syria during the last thirty years (to name just a few, see Sanlaville, 1985; Morandi Bonacossi, 2007; Mantellini et al., 2013). These include three projects directed by the authors in territories situated on the western fringes of the Syrian Desert (Fig. 1):

1. The Arid Margins survey (1996-2010) in the North (Geyer et al., 2006),
2. The Homs Region Survey (1999-2010) in the centre (Philip and Bradbury, 2016),
3. The Leja survey (2002-2009) to the South (Braemer and Davtian, 2017).

These projects have generated a large set of environmental and archaeological data, the formatting of which through databases linked with GIS offers a means to understand the implementation of hydro-agricultural systems, and thus the growth of agriculture in these areas, from the Aceramic Neolithic B (8500-7000 BCE) to the present time. These datasets can offer a nuanced picture of developments within the Fertile Crescent of the Middle East at a microregional scale (Braemer et al., 2009; Geyer et al., 2014; Philip and Bradbury, 2010). However, a major concern for researchers is the need to synthesize data at the macroregional or subcontinental scales, which constitute the current basis of most archaeological-historical narratives. This was one of the aims of two recent international projects, PaleoSyr-PaleoLib (2010-2014) based in France and the Fragile Crescent Project (2008-2012) based in the United Kingdom, members of which present the following results.

These three regions are interesting because all were surveyed at a large scale for both archaeological and environmental features. They also share common physical and bioclimatic components which allows them to be studied as a together. As they are located in a degraded Mediterranean climate zone (Traboulsi, 1981), the main characteristics are those of the Mediterranean climate (two seasons – dry summer, wet winter –, moderate temperature), but with higher contrasts (less rainfall, higher temperature, longer dry season, higher inter-annual and intra-annual variability). They are also characterized by wide surfaces (plains, plateaus, glacis) generally level or gently sloping. Basalts and carbonate bedrock (Jurassic and Cretaceous hard limestones, or Late Cretaceous, Paleogene and Neogene soft limestones) prevail and have a direct influence on soil quality (Table 1). Surface runoff is limited and the main element of the hydrological network flows seasonally. These regions are located in the steppe zone where annual plants and especially annual grasses prevail, without the woodland formations known in the coastal mountain massifs.

Our aim here is to describe the approach taken to improve the methods and the concepts that we use: in contrast to traditional modelling approaches, which often depend upon the downscaling of environmental data established at a continental scale (i.e. drawn from maps of land cover and rainfall), we stress here the need to work from the bottom-up, by generalizing from landscape observations made at microregional level, using common descriptors and qualitative indicators. The water systems discussed are therefore mapped using such a framework. The GIS-based spatial analysis of this data uses a weighted average model derived from field evidence for the different technical choices made (i.e. the decision to utilize specific water management devices) in relation to the different agronomic landscapes.

In the study areas, the major constraint for agricultural development is aridity. In this context, geo-archaeological surveys have highlighted the critical importance of water supply systems (Braemer et al., 2010); these were described, dated, and their areas of influence delineated with high precision (Table 1). A typology of land developments associated with water systems was then established. Each type of development must be consistent with the environmental potential.

Goal of the landscape management	Actions on the ground	Hydraulic installations
Developing the area where water is available	Developing ponds	Natural pools ; stone lining of pools Dams and reservoirs into wadi beds
	Developing access to subterranean aquifer	Natural cleft with rock cut steps gigiving access to the sub-basaltic aquifers or karstic aquifer Wells dug in the rock Wells dug in river beds to the underground flow Karstic resurgence system structuring
	Developing springs and catchments	Spring catchment on low cliffs by 4 to 5 m tunnels and short channels leading to large basins Spring fountains Spring surface basins Spring underground cisterns
Collecting rain streaming	Field installations	Talweg terracing for agriculture Flash floods catchment by long channels Runoff micro-catchment to cisterns
	Building devices	House roof catchment to individual cistern
Diverting the flow of water	Dams	Diversion dam on the river, channel (up to 2 km long) and reservoirs Diversion dam on the river, diversion channel (up to 20 km long) and reservoirs Diversion dam on the river, diversion channel and irrigation system
		Storage dam in river bed (wall reservoir and water channel for irrigation)
	Qanats	River inferoflux Catchment Ground water Catchment
Transporting spring water		Built up aqueducts and reservoir/fountains Simple channel and reservoir Spring catchment by Qanat and canals for irrigation
Storing the water	Cisterns and Basins	Covered cisterns up to 400 m) Arch covered cisterns up to 1700 m3 Open basins up to 3000 m3 Open basins from 3000 to 13000 m3 Open basins from 45 000 to 170 000 m3
Distributing running water in city		Water castle and pipes under pressure Unpressurized pipes Water lifting systems on channels and basins
Distributing water in fields	Water lifting systems	Noria Chadouf
Waterpower use	Water mills with horizontal wheels	Oblique water chute Drop-tower (arubah penstock)

Table I – Functional classification of the various techniques of water management documented in Western Syria (after Braemer et al., 2010).

2. Ways to understand and represent aridity

At the macro-regional scale, rainfall maps offer the best way to convey aridity. These can be combined with maps of vegetation cover to give an accurate representation of the "bioclimatic aridity". In the archaeological literature, however, maps of this type are generally drawn at a very generalized level, either because they are based upon existing schematic climatic maps drawn from standard reference works (e.g. the map in Wilkinson's *Archaeological Landscapes of the Near East*, 2003, p. 18, is based upon the map provided in Beaumont et al., 1976), or supra-continental models (for example, for Saudi Arabia, https://hydrology.kaust.edu.sa/Pages/LSM.aspx) which are, at the best, downscaled to adapt to the local study map.

Wilkinson et al. (2014) defined the very powerful concept of the "zone of uncertainty" which identified a specific bioclimatic area delineated by the 180-300 mm isohyets. This concept has allowed, for example, the reinterpretation of a significant element of the history of urban development in the Fertile Crescent of the Ancient Near East during the Third Millennium BCE. This area, termed 'The Fragile Crescent' by Wilkinson, is characterised by short cycles of growth and collapse in the urban centres that had expanded into the drier agro-pastoral zone. In fact, this area was intensively exploited during an episode that lasted no more than few centuries. However, the published maps of this "zone of uncertainty" are drawn in one case (Fig. 2, a) "based on Wachholtz, 1996" which is at the approximate scale of 1:6.400.000 and for the other (Fig. 2, b) "simplified from the map in Sanlaville 2000" at a scale of approximately 1:21.000.000. Given the degree of regional variation, in topography for example, it is clear, that the concept must be refined spatially if it is to be used at a higher level of accuracy, that is at the micro-geographical level of the archaeological feature. To do this updated rainfall data is required, for example, as recently created by using the longest available series of monthly records from local weather stations (Traboulsi, 2016, 2010, 2004; Laborde and Traboulsi, 2002). Using these new data, the boundaries of the "zone of uncertainty" can be defined more precisely, for example by taking account of the spatial variation in the location of the 200 mm isohyets that occurs between wet and dry years (Fig. 2, c) (Chambrade, 2005).

3. Estimation of agro-pastoral potential

In addition, while working with the concept of "zone of uncertainty", we need tools that can provide a more finely-tuned description of sub zones. The use of standardized descriptors can facilitate inter-area comparisons, and if these descriptors can be used at different scales, they offer a robust way of understanding human subsistence and modes of human activity, such as water harvesting systems, that can make areas more or less attractive.
Our aim is to create a regional reference for estimating:

1. the potential water resource, from natural and/or artificial origin,
2. the land use potential in terms of cultivation and herding. This we do through a synthesis of the known environmental conditions and the constraints identified at a microregional scale. The area of interest covers the medium arid and lower arid bioclimatic zones, a "sub optimal zone" in the terms of Philip and Bradbury (2010). By this we mean a region which while not prime agricultural land, may offer considerable economic potential, but which cannot be realised until specific constraints are removed. Examples would be landscapes where the clearing of surface stone is an initial requirement of cultivation, or where effective human exploitation might first require the construction of water harvesting systems.

A first stage was to investigate small regions (measuring a few dozen kilometers on each side, see fig. 1) where the environmental components can be subject to fine-grained analysis thanks to knowledge acquired through pedestrian geoarchaeological survey: the Arid Margins of Northern Syria (Besançon and Geyer, 2006), Homs region (Philip and Bradbury, 2010, 2016) and the Leja plateau in Southern Syria (Braemer and Davtian, 2013, 2017).

The maps of potential land use were first developed locally taking into account factors such as relief, geology, soils, hydrology, etc., that influence processes such as surface run-off, the flow in watercourses, groundwater, etc. However, account was also taken of changes resulting from the introduction of hydraulic techniques. By doing this, the study is able to highlight long term variations in "attractiveness", as this applies to possibilities around both crop and livestock raising, and thus conditions of land use.

3.1. The Arid Margins of Northern Syria land use example: an attractiveness approach.
In this region surveyed from 1995 to 2010, it has been observed that bioclimatic zoning based on rainfall and the resulting vegetation values is not sufficient in itself to provide an accurate map of the constraints on human activity. This is because they do not explain the large spatial and temporal variability in the expansion of sedentary populations, and in the specific forms of agricultural development. For an improved analysis, we must combine data from different maps: topographic and geomorphological, lithological and superficial facies, soils and water resources (both natural and artificial). As a result, twenty-seven descriptors based on field observations were characterized:

1) five apply to topographic features (T): T1 = hills and gentle slopes of the mountains' upstream watersheds; T2 = valley bottom of the main wadis and *faydas*[1]; T3 = interfluves (mainly on glacis and basaltic mesas); T4 = erosion surfaces (rock pediments, gypseous plateforms); T5 = karstic landforms, enclosed depressions, poljes.
2) six refer to geomorphology and lithology (S): S1 = middle and upper Cretaceous compact limestones; S2 = Oligocene and Upper Eocene limestones; S3 = Helvetian detritic sediments; S4 = Mastrichtian, Paléogene, lower and middle Eocene marly crumbly limestones; S5 = basalt; S6= pliocene sediments.
3) nine refer to edaphic factors[2] (E): E1 = eroded zones, without superficial deposits; E2 = coarse and often cemented superficial deposits; E3 = gypsum crusts and slabs; E4 = marly limestones and chalk, weathered outcrops; E5 = relict soils; E6 = colluvium in valley bottom and lower slopes (terraces); E7 = alluvial deposits in *faydas*; E8 = aeolian deposits; E9 = slope deposits.
4) seven apply to water resources (H): H1 = temporary water locations (residual pools, kamenistas, artificial ponds; H2 = infra basaltic springs; H3 = underground watercourses following the line of major wadis; H4 = *faydas* underground watercourses and gypseous platform artesian springs; H5 = deep ground water; H6 = perennial streams (nahrs); H7 = salted endoreic basins.

By doing this we were able to put climatic aridity into a wider context, and we highlight the weight of the edaphic component that may either increase or compensate for aridity (Besançon and Geyer, 2006).

3.2. An attractiveness map based on the four fundamental constraints of: topographic features, geomorphology and lithology, edaphic factors and water resources.

The aim here is to delimit territorial units that have more or less capacity to meet the needs of cultivators, in effect different grades of attractiveness. The process of seeking to define areas

[1] *Faydas* (local Syrian term) are widened valley bottoms or small plains filled with alluvial silt; they are located at the confluences of wadis or around endoreic basins.
[2] related to or caused by particular soil conditions, as of texture or drainage, rather than the climate.

of attractiveness highlights the complex spatial distribution of arid locations across the region. When the major characteristics of the different environmental components are combined with what is known concerning the effects of anthropogenic pressure on these environments, we are able to define spatial entities sharing similar constraints and offering comparable potentials. From this, we then mapped similar degrees of "global attractiveness" (Fig. 3). Of course, a degree of attractiveness cannot be an absolute value: it is a relative value resulting from an estimate. We also acknowledge that attractiveness is likely to change both by place and over time, even within a single region (see below). This is because attractiveness is the result of both the impact of climatic change on the natural environment, and its influence on anthropogenic activity, especially developments in water management. Thus, the various components described above were evaluated against field observation, and the resulting attractiveness maps produced manually.

3.3. Attractivity and settlement patterns

The second step in the process was to overlay the distribution of recorded human settlement upon the map of attractiveness (Fig. 3). This allowed the identification, at a regional scale of:

1) those areas where systematic settlement throughout the Holocene is correlated with high attractiveness,

2) those areas that score less well on attractiveness, and where land development and water management were clearly a major factor in explaining land use and settlement patterns,

3) areas where the attractiveness score and settlement density appear to be contradictory, and where the situation requires further explanation.

Three examples in which the exploitation of land was directly based upon water harvesting systems illustrate our method.

The major lesson to be drawn from this analysis is that in a general context of low and variable precipitation, edaphic parameters explain the differences better than rainfall. Levels of rainfall are analogous in the Arid Margins, the eastern part the Homs area and in the Leja (more or less 200 to 300 mm/year); in the western part of the Homs area, they reach 400-500 mm/year). We focused on edaphic factors, because they allow a nuanced analysis of the local effect of rainfall. For example, because they have been more extensively weathered, the basalts of the Homs region have higher agronomic potential than those of the Leja.

3.3.1. Neolithic water harvesting systems

In the less attractive areas, the first settlements occur as early as the late/final Aceramic Neolithic B (8500-7500 cal BP). This activity is based upon the exploitation of the *kamenitsas* (dissolution pans on limestone rock) and the creation of ponds in the Isriya Mountains and the Gabal Balas. These limestone mountains are dry, and offer only very a limited surface water resource, but provide high quality seasonal pastures. The use of ponds and *kamenitsas* allowed human groups to occupy these dry areas on a seasonal basis, and during the periods of maximum occupancy of the arid steppe they were used by mobile populations (Geyer and Besançon, 2013; Geyer et al., 2014).

3.3.2. The distribution of the population and land use during the Early Bronze Age IV

During the Early Bronze Age IV (2500-2000 BC), the main technical innovation was the digging of wells on the basaltic *mesas* of the Gabal al-Ala and the Gabal al-Has. These surfaces, although fertile, remained of limited attraction to sedentary populations because of the difficulty of maintaining a regular supply of water for human and animal consumption. The purpose of water storage in these areas was not –and still is not– irrigation, but rather to have water available for human and animal consumption. Cereal cultivation is rainfed as a rule. Water storage systems allow the settlement of humans and enhance the capacity to feed and water animals. The subsequent cutting of wells into the basalt geology removed this constraint, making it possible to establish villages and transform the *mesas* into a considerably more attractive area. Once this technology was established, it proved possible for long-term occupation by sedentary populations to spread across all those zones that could offer this possibility. (Geyer, 2009).

3.3.3. The Byzantine period - "the Eastward expansion"

The Byzantine period (450 – 632 AD) corresponds to the maximum spatial extent of sedentary settlement. While the very high level of attractiveness of the basaltic mesas continued, the widely documented expansion of settlement to the East was based upon:

1) the creation of the *qanat* network which enhanced the attractiveness of the central lowlands (great *fayda*),

2) the digging of hundreds of cisterns allowing the development of livestock raising across a large extent of the eastern part of the area, a region that had hitherto been of low attractiveness (Geyer et al., 2016; Rousset, 2010; Geyer and Rousset, 2001).

3.4. Water harvesting systems adapted to environmental constraints

Comparing the different water harvesting systems identified in the Arid Margins with the different attractiveness areas, it is obvious that these systems were adapted to the environmental constraints (Fig. 4):

–wells primarily enabled the spread of settlement into areas where attractiveness was high to very high, i.e. where intensive agricultural development was facilitated by abundant water resources and the most fertile land;

–qanats were predominantly located in areas of medium attractiveness, where water resources were less abundant, and where they must be concentrated and, above all, directed to irrigate the most fertile areas;

–cisterns, ponds and *kamenitsas* were employed in areas of low attractiveness, where the resource was scattered and of uncertain reliability, and where development was focused primarily on livestock breeding, with the exception of some particularly favoured microregions that allowed cultivation within a very limited area.

The key point is that the potential offered by the natural environment was enhanced by the use of water harvesting systems. In fact, water management appears to have been the key determining factor in transforming the potential of the natural environment over time. The harsh character of the zone concerned was ameliorated by these adaptations, and its constraining effect on human activity reduced. The result was to render the area suitable for a process of colonisation either through the sedentarization of mobile populations, or by expansion into the area of existing sedentary populations which could become permanent and thus witness to a transformation of the original environmental conditions as these related to the occupation of land, human settlement and its economic exploitation (Geyer, 2009).

3.5. Favoured types of water management vary across the landscape

The types of water management employed are directly related to environmental conditions, being responses to climatic and edaphic aridity. They determine patterns of development based on the potential of each area (Fig. 5). Thus, in the western part of the region where rainfall is sufficient to support crops, the primary role of the wells is to supply regular drinking water. In contrast, at the eastern end of the region where the degree of aridity meant that the area could support only nomads practising mobile livestock raising and small scale agriculture, cisterns provide a similar function. In both cases, the natural input relating to aridity shapes the specific type of development. This development is, ultimately, of secondary importance because it cannot change drastically the influence of the natural input. Between these two extremes, various uses are attested: irrigation using qanats to grow annual crops and even trees, cisterns used primarily to water livestock intended for meat-production in the context of sedentary occupation. The ponds and *kamenitsas* used in the Neolithic remain in use today, and while these were initially used by hunters, they were eventually refocused upon the sustenance of mobile livestock herds.

Similar analyses made for Northern Syria and Southern Syria allow the comparison of the changes in both regions, and underline the fact that changes in settlement patterns in arid zones are not only governed by variations in precipitation, but by a wider set of factors. Each one of these has an impact that we are able to identify and sometimes to measure. For example, the spatial impact of water harvesting systems can be delimited (Braemer et al., 2016). The major conclusions of this analysis, in a general context of low and variable rainfall are: 1) that the edaphic factors are prevalent on the rainfall parameter as regards the choice of settlement location because they allow a nuanced analysis of the local effect of the precipitation, 2) that water harvesting systems designed to store water for human and animal consumption are the rule, with irrigation systems much less frequent.

4. Working at a macro-regional scale

Initial studies in Northern and Southern Syria were made separately, relying on maps and environmental data designed specifically for each region. Of course, this means that a direct comparison between settlement processes in these areas will not use the exact same parameters. To consider the whole of western Syria a different approach is required, one that can integrate the small-scale mapping of the various constraints that shape landscape potential and water management techniques. Therefore, we propose a new phase of analysis, one that uses a unique GIS framework. In this case, the layers are based upon maps available at the regional level, morpho-soil (made from Cherkess, 1954-64; Gèze, 1956), geology (Ponikarov, 1966), rainfall (Laborde and Traboulsi, 2002), that have been rasterized with a pixel-size identical to that of Landsat image one (scenes: 17403520000622, 17403620000622, 17403720000622 on 22.06.2000, day’s date 06/22/2000). This combines spatial accuracy with the possibility of visualization at multiple scales.

The ultimate objective is, of course, to create new maps that synthesize qualitative elements that will allow us to grade each sub-area as more or less attractive for cultivation and pastoral activity. In effect we are producing a map of agronomic potential. The definition at local level, of "quality categories" for soils which appear homogeneous when viewed at a sub continental scale, is the main challenge. To obtain homogeneity it was necessary to reduce detailed description by grouping soils into a small number of macro-categories (in this case five). This allows specific local observations to be encompassed within a standard framework (Table 2). This approach both supports the comparison of regional patterns when these are subject to different local environmental characteristics, and offers a simplification of the categories. The three geographical areas we wish to compare are all subject to a common degraded Mediterranean climate, but are subject to different specific constraints. For example, annual mean precipitation is higher (> 400mm/year), in the western part of Homs region because of its location at the eastern end of the "Homs-Tripoli gap", than the in the eastern part of Homs region (the Arid Margins) and the Leja (each with 200-300mm/year). Equally, while there are areas of basaltic geology in parts of all three study regions, the age of the lava flows varies, as does the degree of alteration, producing soils with different qualities.

4.1. Comparison between the Arid Margins, Homs area and Southern Syria (Leja)

We ran an unsupervised automatic classification of the Landsat image which resulted in 20 colour classes, that indicate gradations of surface reflectance. We selected 3 ‘windows’ corresponding to the 3 field study areas (Fig. 7) and, using both our morpho-soil map and our field knowledge, described each colour class in each window by ground surface types (differences in soil depth, moisture and land use). We have observed that differences in identifying and qualifying a colour in a window are mainly due to differences in the geological substratum (basalt, soft or hard limestone), soil morphology, soil moisture and anthropogenic surface features (e.g. roads, buildings). After eliminating the latter, each geological substratum / land surface category was then analysed separately and a "quality" label was assigned using a 5-point scale: sixteen such classes were defined (Table 2). Finally, these sixteen classes were grouped into 5 broader grades on the basis of their agronomic potential. The definition of each class was also discussed in light of observation from detailed field survey, which proved very important. For example, this underlined the fact that there is little pedogenesis on hard limestones, because in arid regions pedogenesis is slow and weathering very high, thus hindering deep soil development. It is relatively easy to make changes or additions to our definitions and so model can be re-run to produce updated maps, as our knowledge advances. This model of graded agronomic potential can easily be generalized and extended to the entire northern Levant (Fig. 6).

Table 2 – Agronomic potential classes clusters.

Agronomic clusters/geology	Definition of the agronomic clusters
Water	Water
Basalts Agronomic potential A	Class (Cl) 8, 12, 15, 17, 19 on basalts: High yield, often irrigated crops on deep soils. Natural woodlands (trees, shrubs) by place
Basalts Agronomic potential B	Cl 3, 7, 11 on basalts: High yield crops on developed soils and at the bottom of the valleys.
Basalts Agronomic potential C	Cl 16, 18 on basalts: Dry-farmed crops on well hydrated soils
Basalts Agronomic potential D	Cl 6, 9, 10, 13, 14, 20 on basalts: uncultivated areas, rocky surfaces, dry and low yield interstitial crops
Basalts Agronomic potential E	Cl 4: anthropogenically modified areas, generally built-up
Soft Limestone/surface formation Agronomic potential A	Cl 11, 8, 12, 15, 17, 19 on Soft Limestones and surface formation: High yield, often irrigated crops on developed soils
Soft Limestone/surface formation Agronomic potential B	Cl 16, 18, 3, 7 on Soft Limestones and surface formation: High yield crops on developed soils
Soft Limestone/surface formation Agronomic potential C	Cl 13, 14, 20 on Soft Limestones and surface formation: dry-farmed crops on medium hydrated soils
Soft Limestone/surface formation Agronomic potential D	Cl 6, 9, 10 on Soft Limestones and surface formation: uncultivated areas, rocky surfaces, dry and low yield interstitial crops by place
Soft Limestone/surface formation Agronomic potential E	Cl 4 on Soft Limestones and surface formation: anthropogenically modified areas, generally built-up
Hard Limestone Agronomic potential A	-
Hard Limestone Agronomic potential B	Cl 3, 11, 12, 19 on Hard Limestones: Woodlands and terraces arboriculture
Hard Limestone Agronomic potential C	Cl 7, 8, 17 on Hard Limestones: open forests, bush, reforestation
Hard Limestone Agronomic potential D	Cl 6, 9, 10, 13, 14, 20 on Hard Limestones: rocky uncultivated areas, poor soils, scanty vegetation
Hard Limestone Agronomic potential E	Cl 4 on Hard Limestones: anthropogenically modified areas, generally built-up

An examination of the distribution of the pixels of each class in each window, allows the surface extent of each class to be measured and the different classes to be compared. For example the ratio of the total surface extent of classes A and B – which offer the most favourable conditions for agricultural development – against the total surface extent of classes C, D, and E – the less favoured categories – differs between the different study areas. In the Homs region the ratio is 60:40, compared to 43:57 in the Leja, and 13:87 in the Arid Margins. This ratio highlights very neatly the difference in potential between the three areas, and may provide a reasonable proxy indicator for the 'value' of land in each area, and perhaps even the desirability of bringing specific areas under political control.

4.2. Combining layers: soil classification and water resources

We are now in a position to combine this map of agronomic potential which gives a derived edaphic value to each pixel, with different sets of reference data (bio-climatic classes, water resources, etc.). A raster image of this cartographic arrangement can then be used as a homogeneous and controlled common basis to discuss similarities and differences between zones. As seen above, the count of pixels in each category allows a very basic quantification of the potential of an area. In addition, we can now factor-in water harvesting systems that appear at different points in time, allowing the changes in landscape value that these introduce, to be included within the model. This opens the way to a comparative historical analysis of the different landscapes.

Firstly, we selected from our archaeological database, the wells, cisterns, and open reservoirs that had been identified in the three areas. The "big picture" highlights marked differences in the occurrence of each class, not only between areas, but also within each area (Fig. 7). Interpretation of the map that results from overlaying the distribution of water harvesting devices on that showing agronomic potential, is not straightforward. We wish to know within which of the quality classes each water device is located, and this cannot be established from visual inspection of the general map because the pixel-size of the raster image is very small: 28.5 x 28.5 m. However, this can be calculated using the GIS (Table 3 and Fig. 8).

The first important observation is that water harvesting devices are preferentially located in agronomic classes C, D and E, that is those areas with the least agronomic potential. This point is readily confirmed by calculating the density of water management devices per km^2. A first explanation might be that these devices – which make water available for daily consumption and the watering of garden plots - and the settlements to which they are linked, were located next to the favoured agronomic zones in order to preserve these surfaces. This is obvious in the Arid Margins where these devices are all in zones assigned to classes D and E.

This observation is not new, but with our maps we are able to both quantify and understand the spatial dimension of this evidence.

Table 3 – Density per square kilometre and ratio of water harvesting systems in classes A-B and C-D-E for the three study areas.

	Surface of A-B classes (km2)	Total number of water harvesting devices in A-B classes	Ratio of water harvesting devices in A-B/C-D-E classes	Density of water harvesting devices/km2 in A-B classes	Surface of C-D-E classes (km2)	Total number of water harvesting devices in C-D-E classes	Ratio of water harvesting devices in C-D-E/AB classes	Density of water harvesting devices/km2 in C-D-E classes
Leja	785,53	10	4,35	0,01	1041,76	220	95,65	0,21
Arid Margins	511,08	11	2,35	0,02	3287,31	457	97,65	0,14
Homs region	233,35	31	44	0,13	156,44	40	56	0,25
Total	1529,96	52	6,76	0,03	4485,51	717	93,24	0,16

Other differences between the three study areas can be pointed out. In the Arid Margins, some devices are more numerous in particular zones: e.g. wells in the western zone, qanats and reservoirs in the central area, and cisterns in the East. But, even if all the types of device do exist in all three sectors (Fig. 8b and 9b), a strikingly high proportion and density of all types of devices occur in class D (low attractiveness). The geoarchaeological survey in this zone revealed that its agronomic potential could be substantially enhanced if additional water resources could be mobilized. In class E, we find mainly wells, i.e. devices adapted to the daily water consumption of humans and animals.

In the region of Homs (Fig. 8d and 9d) the situation is more mixed. The fact that this region has witnessed intensive cultivation since at least the Roman period, means that traces of small scale ancient water-management infrastructure are likely to have been long since obliterated. Reservoirs are distributed across classes A, B and C, but, by preference, these are located in class A, which represents areas of high agronomic potential on fertile basaltic soils where surface water resources are low, but where this can be effectively compensated by artificial resources. Cisterns are located in classes D and E, i.e. the more arid areas within the marl zones, areas with relatively low agronomical potential. In fact, these are mainly associated with an ancient network of small, probably seasonal, watercourses, many of which have been only marginally active in recent decades. Although Bronze Age tell sites are present along the major wadis, this zone appears to have been more intensively developed during the Roman period, as evidenced by the construction of the cisterns, presence of rural settlements and agricultural installations such as donkey mills and olive presses (Philip and Bradbury, 2016).

In the Leja (Fig. 8c and 9c) the equal distribution of all categories of installation in classes C and D is related to the morphology of lava flows which govern the availability of water. Wells, generally associated with villages, are located in the southern and western zones where the groundwater table is high. Reservoirs and cisterns, which are linked to surface runoff, are concentrated around seasonal watercourses on the edge of the lava flow, or rocky surfaces in the central part of the Leja (Braemer et al., 2016).

When we try to create a general synthesis of the data from the three regions (Fig. 10), there emerges a clear difference between the spatial distribution of reservoirs on one hand, and that of cisterns and wells on one another. Reservoirs are generally more adapted to crop raising, with cisterns and wells being concentrated in the most arid areas. However, there is an anomaly in zones C and E where the density of cisterns decreases and that of wells increases. This observation, we cannot yet explain.

5. Conclusion

The differences in soils and morphology between the various regions represent a first and partial key to explaining the spatial distribution of water harvesting systems. Geomorphological and hydrogeological contexts affect the spatial distribution of water systems. But similar technical solutions (water management devices) can be used in these different contexts: for example, subterranean water runs in a similar way in karst and basalt geology, so similar technics have been used in both contexts. These components are included in our remote sensing analysis; they were studied in detail in each region (especially, Besançon et Geyer, 2006 for the Arid Margins; Philip and Bradbury, 2010, 2016 for the Homs region; and Braemer and Davtian, 2013, 2017 for the Leja plateau in Southern Syria).

Other keys can be proposed. Reservoirs and qanats depend on upstream and downstream water systems that are more extended and complex than those feeding wells and cisterns. The former therefore require a better understanding of the regional topography, and greater territorial control, a factor which may have a social or political dimension. Wells and cisterns offer interesting case studies of the use of water, because they can support both small sedentary agglomerations and the livestock herds of pastoral groups. The pattern of water use may be the key to understanding local variations.

To conclude, we argue that the choice made between different types of water harvesting device does not reflect a dominant "hydraulic culture". In fact all the major technical inventions relevant for water management seem to have existed in Syria no later than the 4th millennium BCE, with the exception of the qanat system which does not appear before the Hellenistic-Roman period (300 BCE-400 CE). The basic technical knowledge was already in existence and could readily be transmitted. At this point, the choices made were mainly shaped by local conditions (geology, topography) which lead to the use of natural surface runoff (for cisterns and reservoirs) or accessing the water table (for wells). The availability of the resource is the primary factor that underpins the technical choice. This evidence was established at regional scales in the Arid Margins (Besançon and Geyer, 2006; Geyer et al., 2006), and subsequently in Southern Syria (Braemer et al., 2009). By demonstrating that a similar pattern can be detected in the landscape of Homs region which lies in the Orontes Valley, we are able to suggest that it may well apply across much of Western Syria, and that the choices made were more opportunistic and situation-dependent than culturally determined.

We must emphasize the resilience demonstrated by past societies and their capacity to exploit water harvesting and storage solutions established by their ancestors. Wells, cisterns, and reservoirs are “ageless” technical devices because they can be managed by small human communities. These were a crucial element in transforming the potential of the natural environment and thus make it suitable for long term settlement: with these devices the area becomes less difficult to exploit, and the constraint placed by aridity is reduced. As a result, a much larger area is opened to exploitation by human groups, and shift that can be permanent and can transform the original land conditions (Geyer, 2009). Even after centuries of abandonment, these areas can be re-occupied by new populations who will derive benefit from these ancient anthropogenic resources.

Acknowledgments

This study of the impact of water harvesting systems on land cover and land use during the Holocene in Western Syria was built upon a prior series of regional geo-archaeological surveys. The synthesis of this data forms part of the *PaleoSyr / PaleoLib project: Holocene palaeo-environments and settlement patterns in Western Syria and Lebanon*, which was funded by the French National research agency from 2010-2014. The analysis of data from surveys in the Homs region forms part of project *The Vanishing Landscape of Syria* which was supported by the Leverhulme Trust (Grant F00128/AR). The *Fragile Crescent Project* was funded by the Arts & Humanities Research Council grant number AH/F010095/1.

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Fig. 1 – Map of Syria showing location of study areas.

Fig. 2 –a = Map showing 'zone of uncertainty within Syria (Wilkinson et al., 2014; based on Wachholtz, 1996, fig. 2.1); b = Middle Eastern area with mean annual rainfall between 200 and 300 mm (Wilkinson et al., 2014; simplified from Sanlaville, 2000, fig. 21); c = Extent of spatial variation of the 200 mm isohyet from wet years to dry years (Chambrade, 2005).

Fig. 3 – Map of Arid Margins survey area showing landscape graded by levels of attractiveness and the distribution of settlement; the three highlighted areas show markedly different densities of settlement.

Fig. 4 – Map of Arid Margins survey area highlighting the water storage system that is most characteristic of human activity in each of the three zones.

Fig. 5 – Arid Margins: water systems and water use.

Fig. 6 – Map showing agronomic potential of Western Syria and Lebanon: Landsat scene automatic color classification with ISOCLUST method under TerrSet - Idrisi (Step1) cross-classified with soil information (Step2) and agro-climatic parameters (Step3). Source: Landsat 8 (color resolution 28.5 m /black and white resolution 14.5 m), scene: 17403520000622, 17403620000622, 17403720000622 (day's date 06.22,2000).

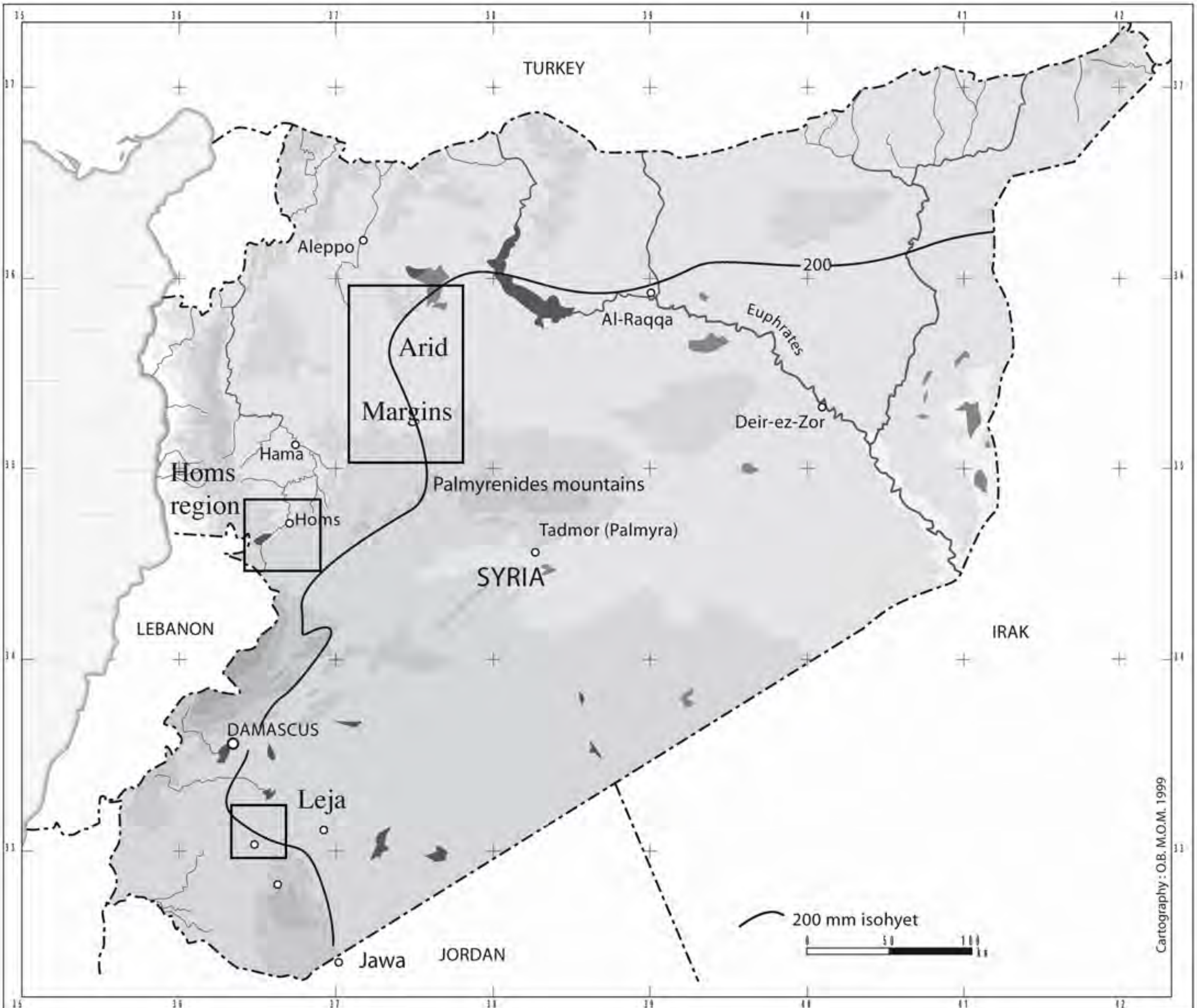
Fig. 7 – The three study areas showing agronomic potential (derived from soil data) and the distribution of water storage devices.

Fig. 8 – Cisterns', wells' and reservoirs' density grouped by class of agronomic potential: a) all areas; b) in the Arid Margins; c) in the Leja (Southern Syria); d) in the Homs area.

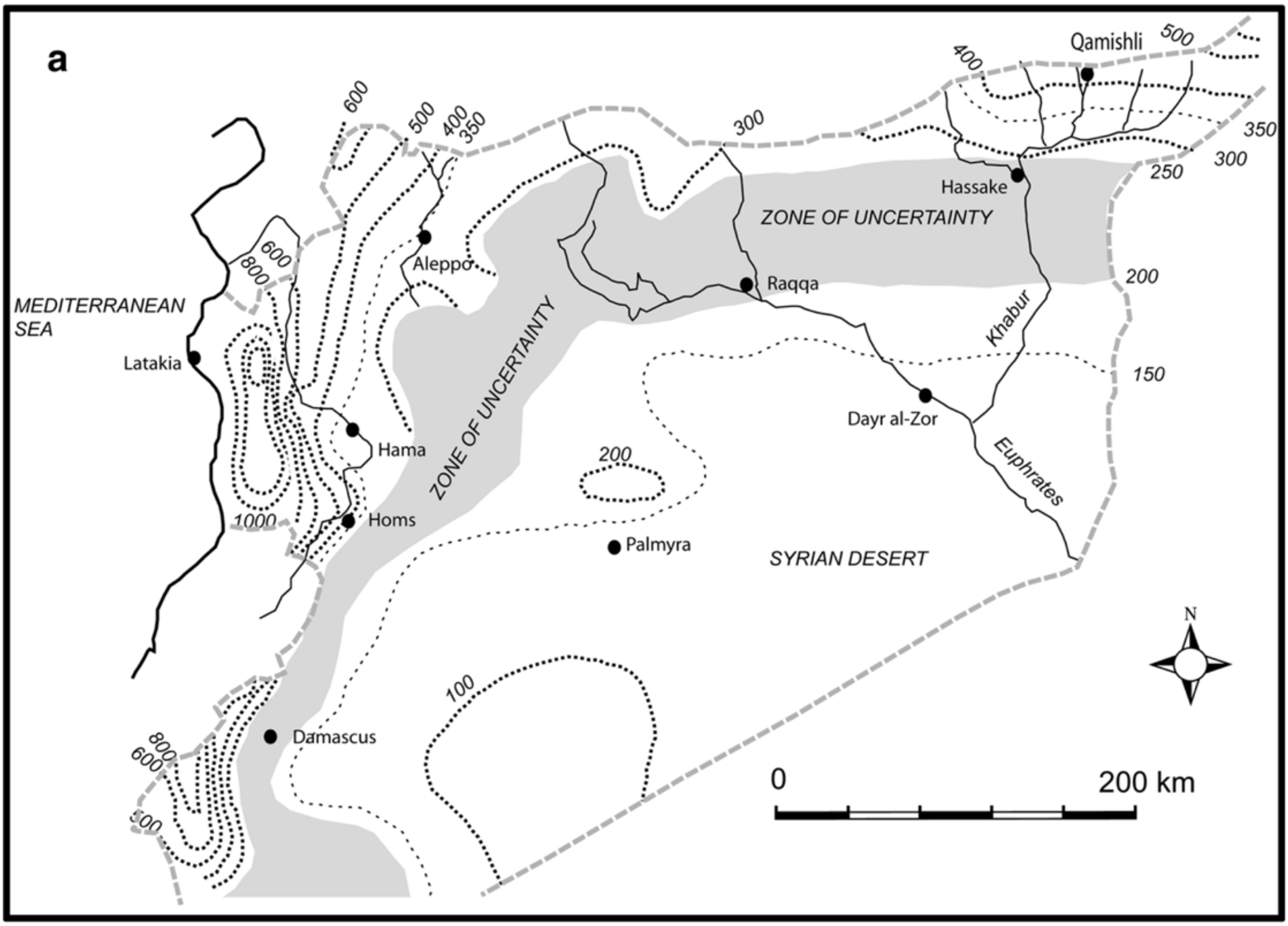
Fig. 9 – Proportion of cisterns, wells and reservoirs: a) in the 5 classes of agronomic potential

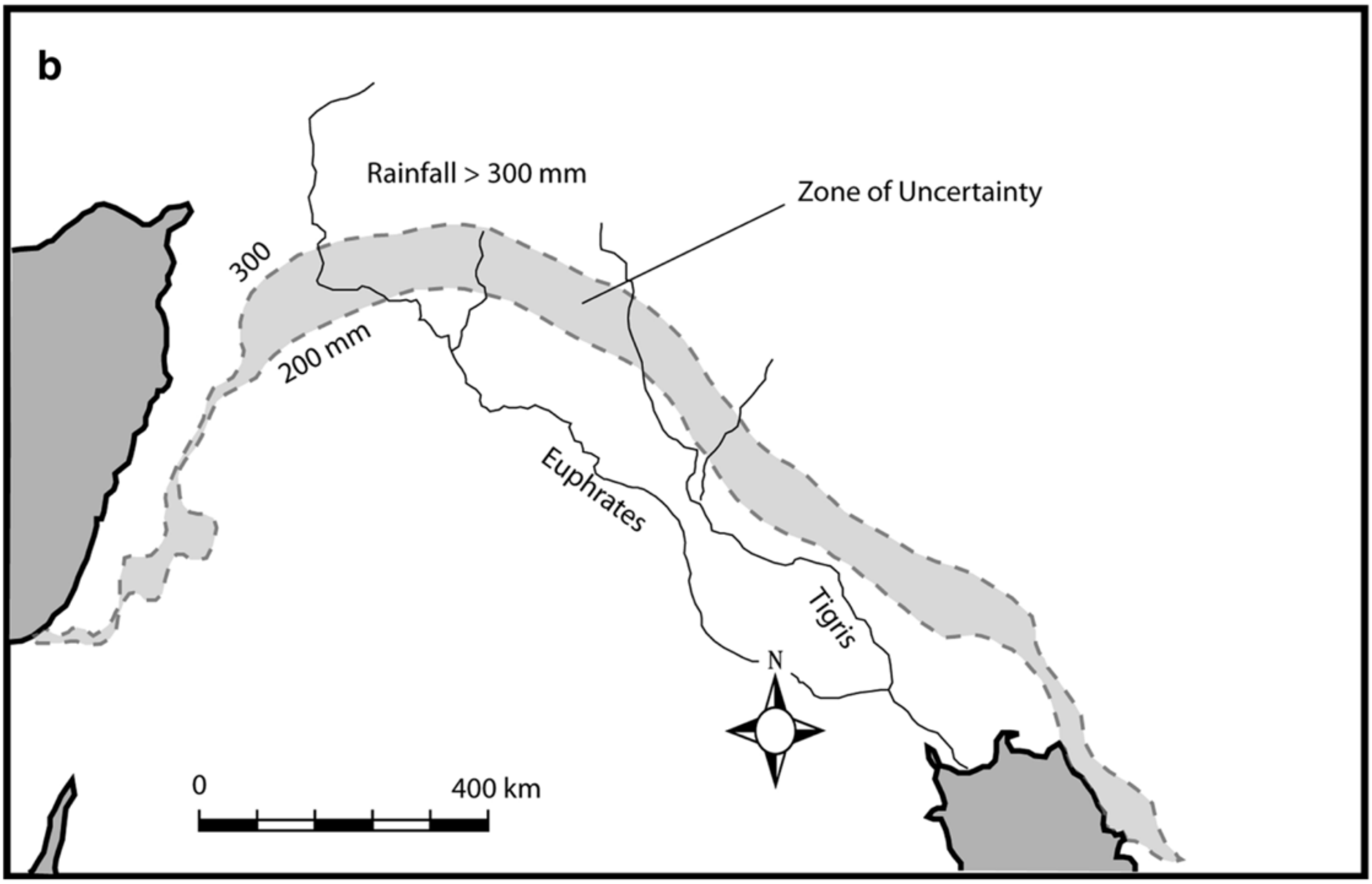
(all areas); b) in the Arid Margins; c) in the Leja (Southern Syria); d) in the Homs area.

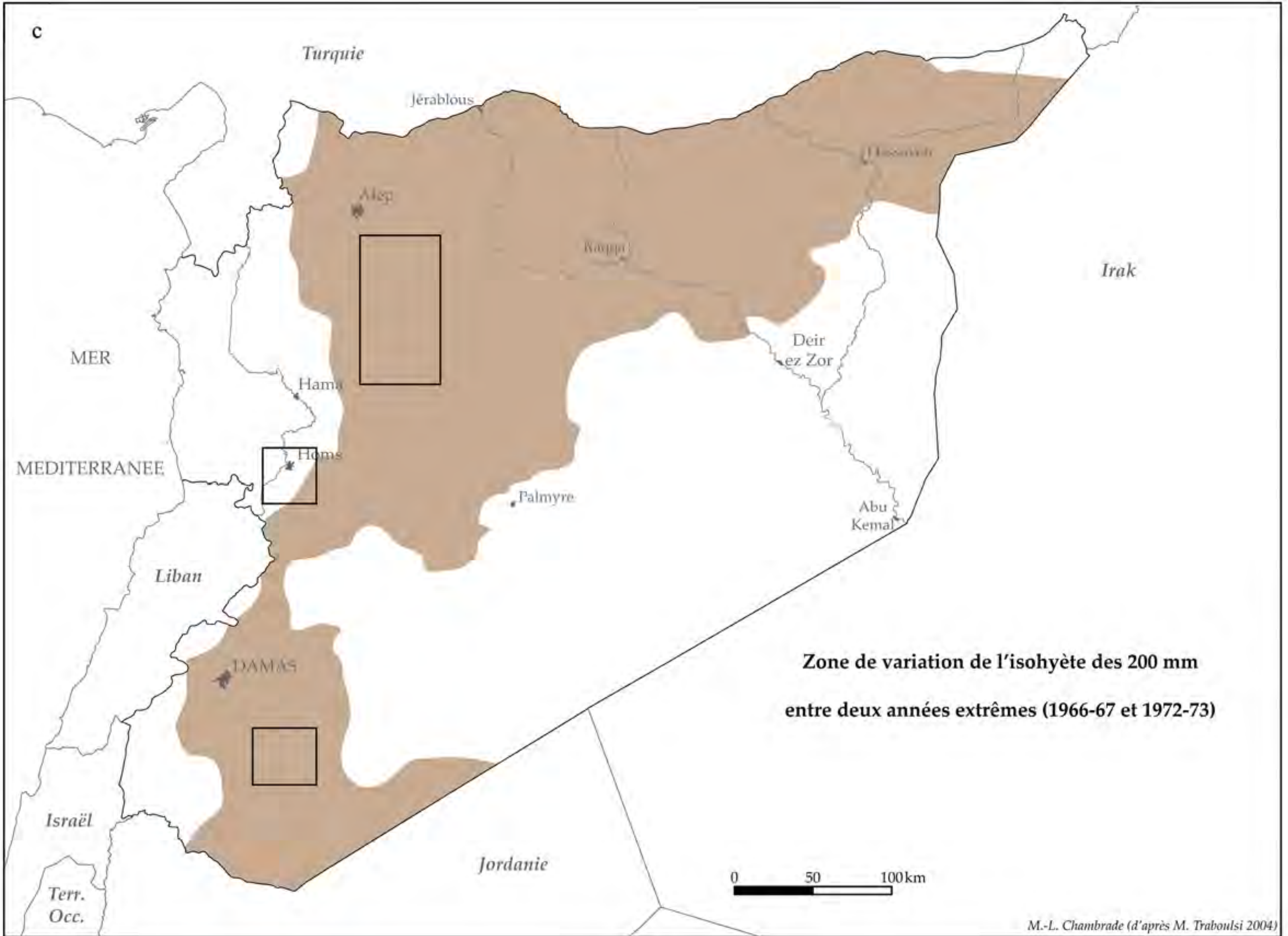
Fig. 10 – Synthesis of the water harvesting systems based on agronomic potential classes.

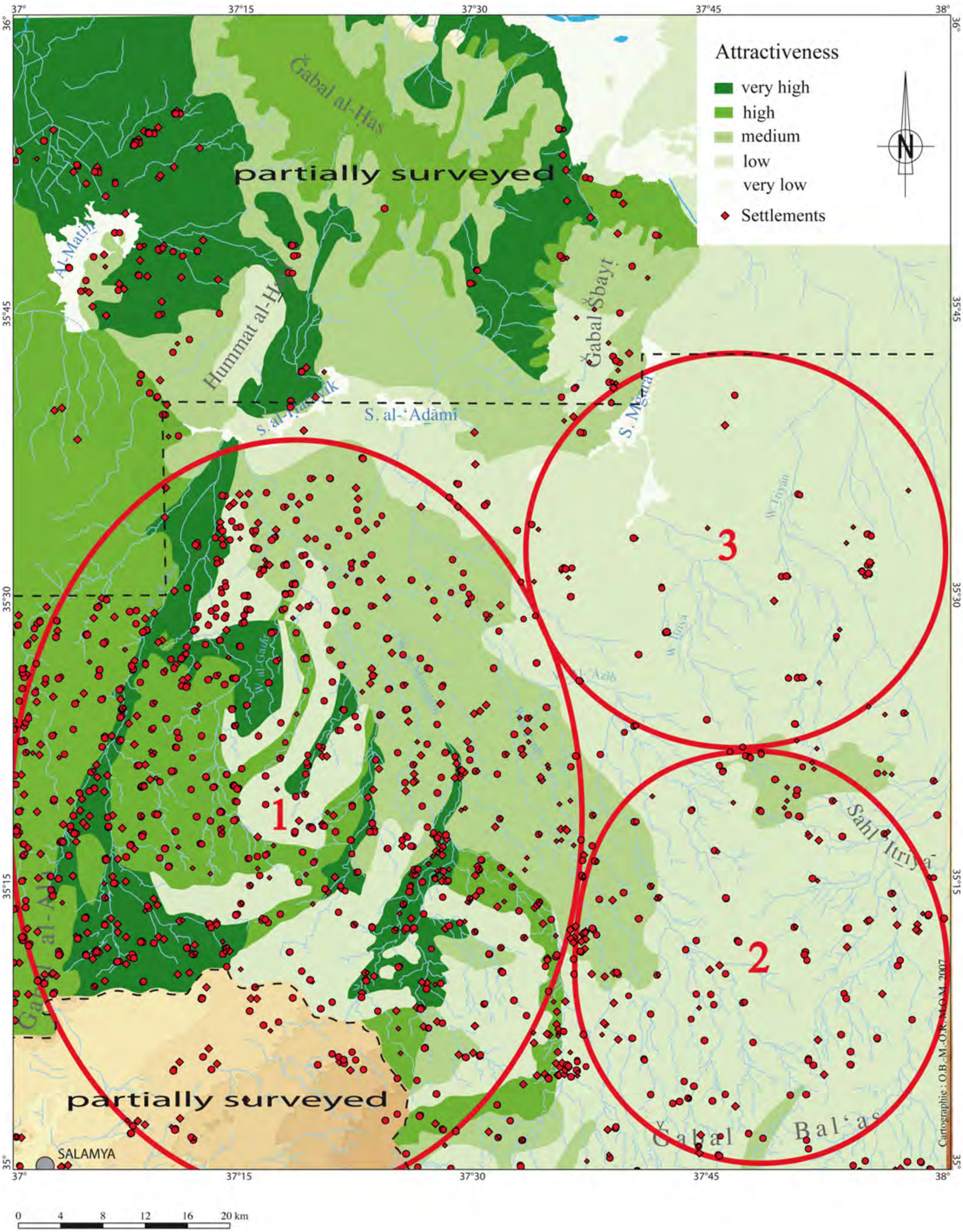


TURKEY
Aleppo
200
Al-Raqqa
Euphrates
Arid
Margins
Deir-ez-Zor
Hama
Homs
region
Homs
Palmyrenides mountains
Tadmor (Palmyra)
SYRIA
LEBANON
IRAK
DAMASCUS
Leja
Jawa
JORDAN
200 mm isohyet
Cartography : O.B. M.O.M. 1999

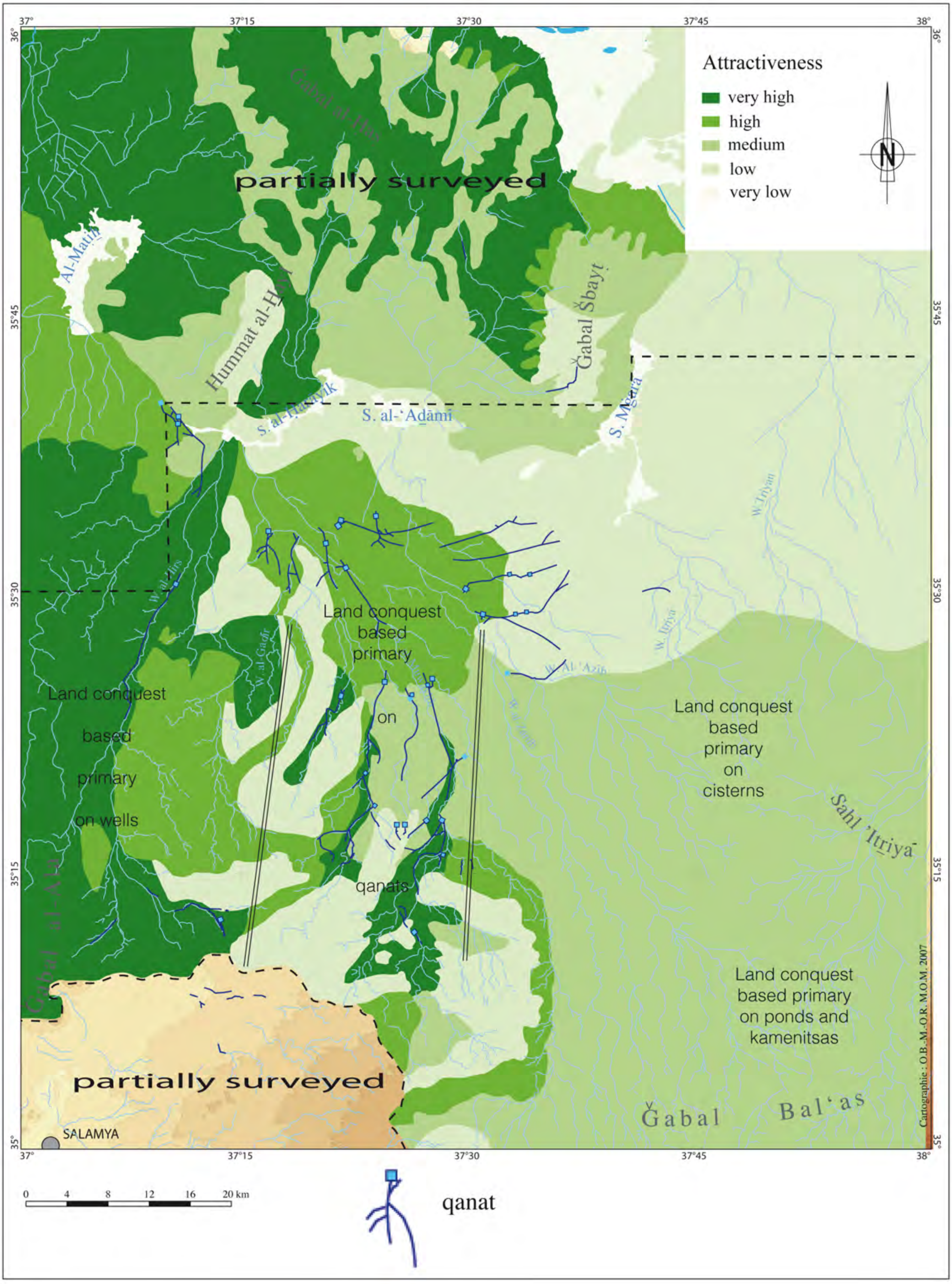

a
MEDITERRANEAN SEA
Latakia
Aleppo
Hama
Homs
Damascus
Palmyra
Raqqa
Hassake
Qamishli
Dayr al-Zor
Khabur
Euphrates
SYRIAN DESERT
ZONE OF UNCERTAINTY
ZONE OF UNCERTAINTY
600
500
400
350
300
250
200
150
100
800
1000
N
0
200 km


b
Rainfall > 300 mm
Zone of Uncertainty
300
200 mm
Euphrates
Tigris
N
0
400 km

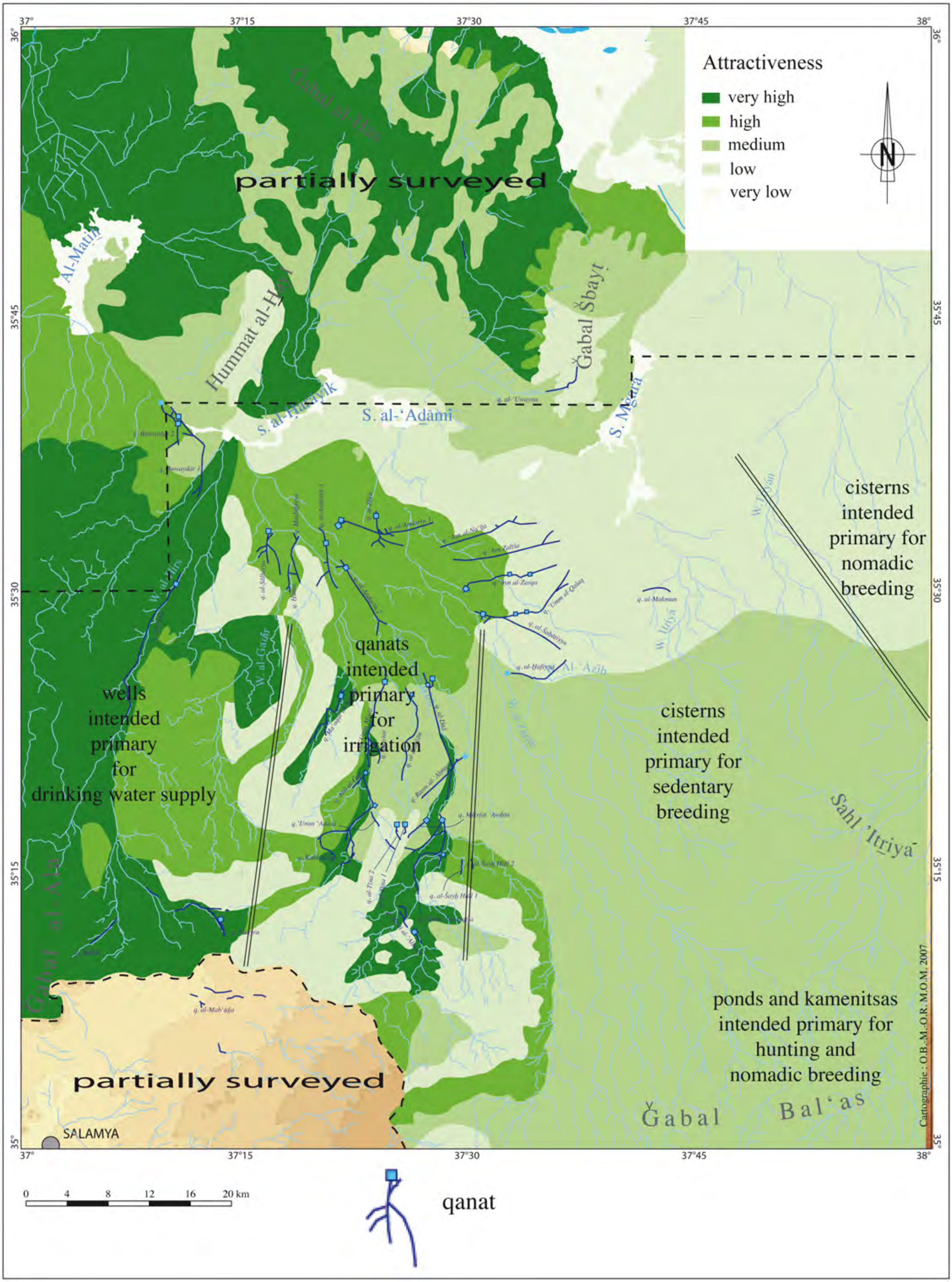

c
Turquie
Jérablous
Alep
Irak
MER
MEDITERRANEE
Hama
Homs
Palmyre
Deir
ez Zor
Abu
Kemal
Liban
DAMAS
Israël
Terr.
Occ.
Jordanie
0
50
100km
Zone de variation de l'isohyète des 200 mm
entre deux années extrêmes (1966-67 et 1972-73)
M.-L. Chambrade (d'après M. Traboulsi 2004)



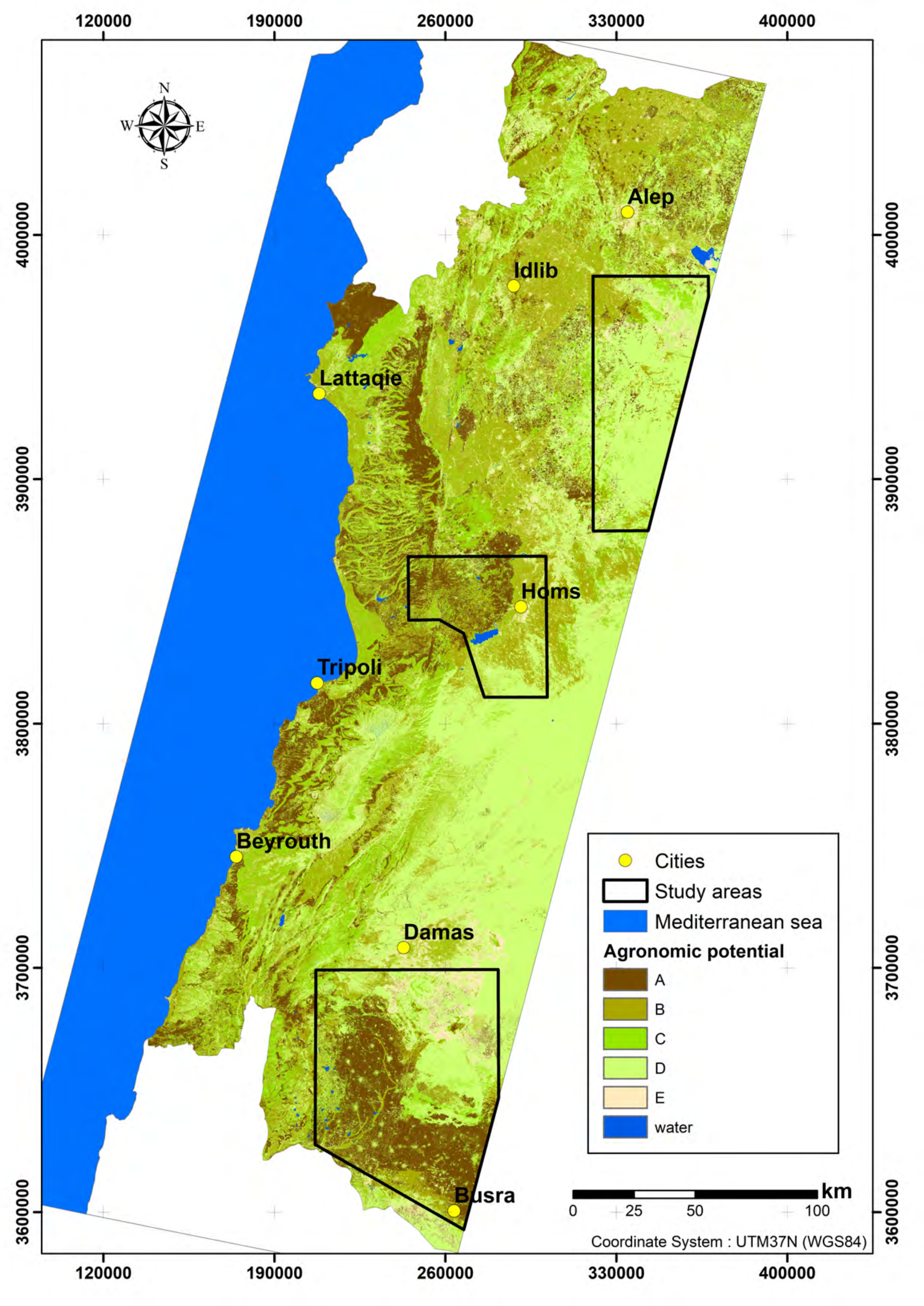
Attractiveness
very high
high
medium
low
very low
Settlements
N
partially surveyed
partially surveyed
Ğabal al-Has
Al-Matiḫ
Hummat al-Hays
Ğabal Šbayt
S. al-ʿAdāmi
S. Mgara
SALAMYA
Sahl ʿItriya
Ğabal Balʿas
1
2
3
37°
37°15
37°30
37°45
38°
36°
35°45
35°30
35°15
35°
0
4
8
12
16
20 km
Cartographie : O.B.-M.-O.R. M.O.M. 2007



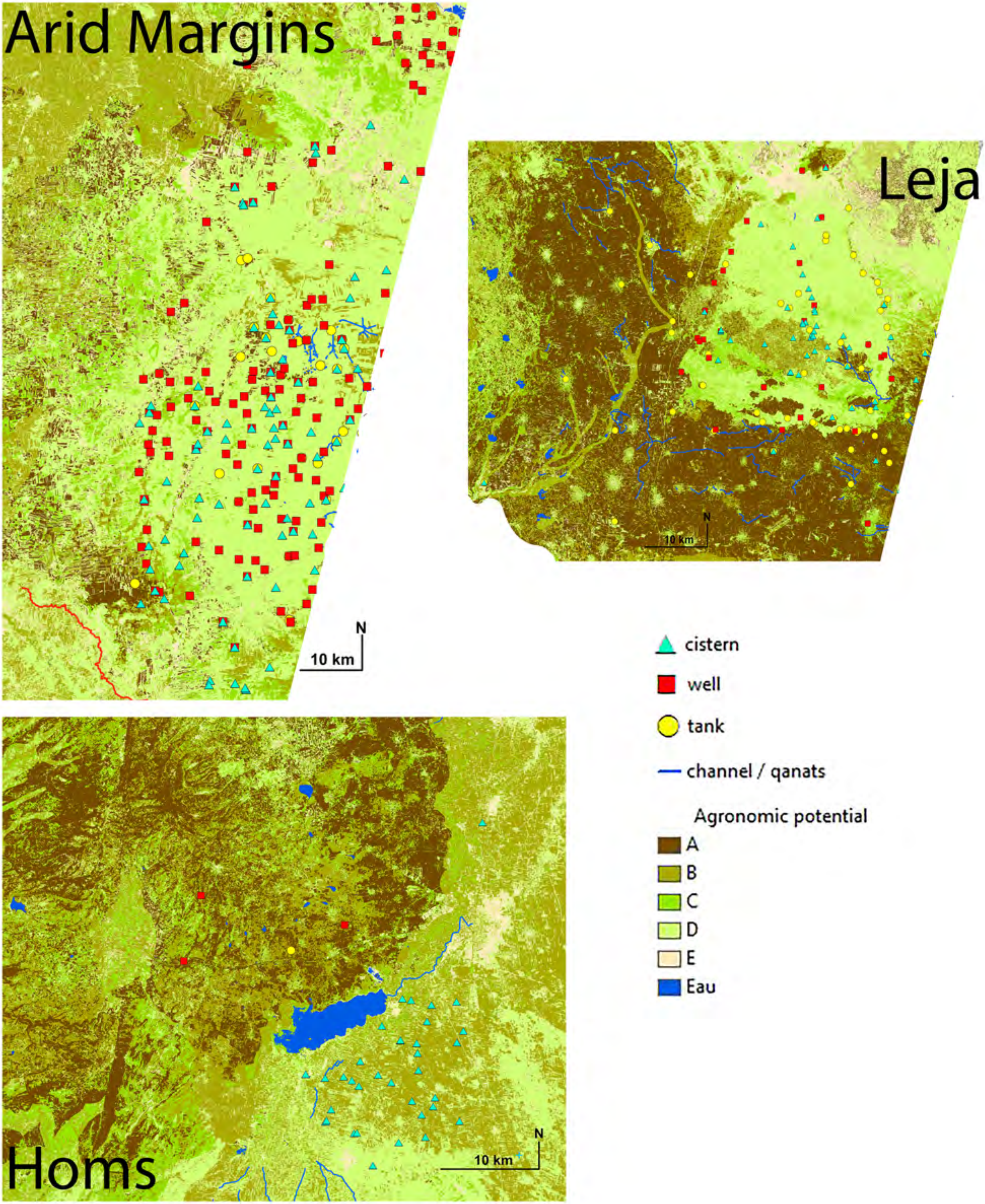
Attractiveness
very high
high
medium
low
very low
N
partially surveyed
Ǧabal al-Bāʿ
Al-Matiḫ
Hummat al-Hayl
Ǧabal Šbayṭ
S. al-Haqlik
S. al-ʿAdāmī
S. Mġara
W. Itriyan
W. Itriya
W. Al ʿAzib
W. al-Gadir
Land conquest based primary on qanats
Land conquest based primary on wells
Land conquest based primary on cisterns
Sahl ʾItriya
Land conquest based primary on ponds and kamenitsas
Ǧabal al-ʿAla
Ǧabal Balʿas
SALAMYA
37°
37°15
37°30
37°45
38°
36°
35°45
35°30
35°15
35°
Cartographie : O.B.-M.-O.R. M.O.M. 2007
0 4 8 12 16 20 km
qanat



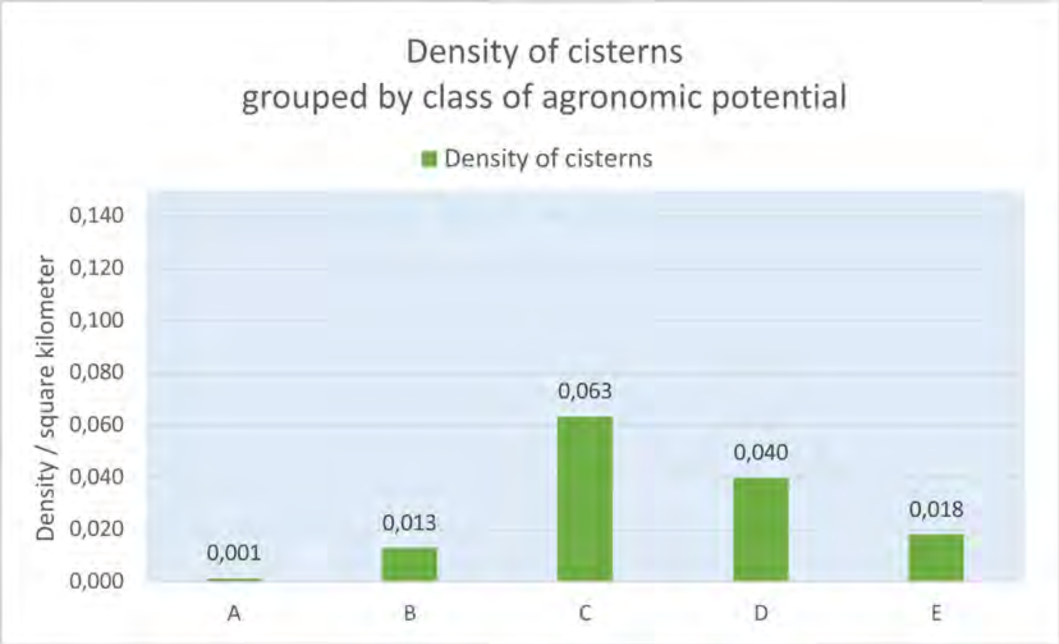
Attractiveness
very high
high
medium
low
very low
N
partially surveyed
Gabal al-Has
Al-Matiḫ
Hummat al-Ḥaǧǧ
Gabal Šbayṭ
S. al-Hasayik
S. al-ʿAdāmi
S. Mġāra
cisterns intended primary for nomadic breeding
qanats intended primary for irrigation
wells intended primary for drinking water supply
cisterns intended primary for sedentary breeding
Sahl ʾItriya
ponds and kamenitsas intended primary for hunting and nomadic breeding
Gabal Balʿas
Gabal al-ʿAla
partially surveyed
SALAMYA
W. al-Gaḥr
W. Itriya
Al-ʿAzib
Cartographie : O.B.-M.-O.R. M.O.M. 2007
37°
37°15
37°30
37°45
38°
36°
35°45
35°30
35°15
35°
0
4
8
12
16
20 km
qanat



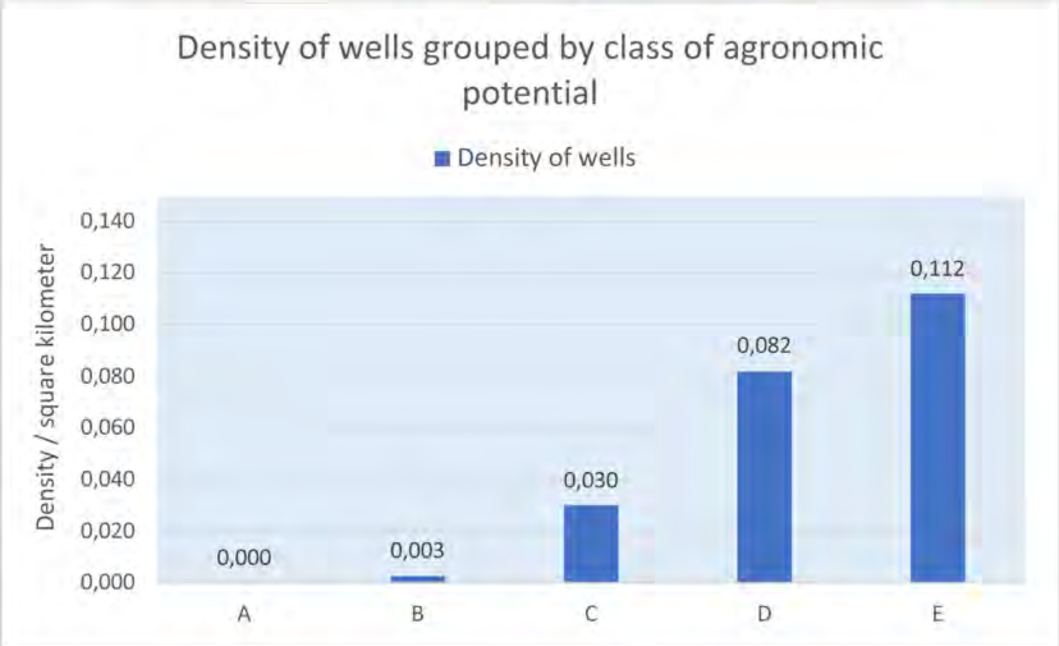
120000
190000
260000
330000
400000
N
S
W
E
4000000
3900000
3800000
3700000
3600000
Alep
Idlib
Lattaqie
Homs
Tripoli
Beyrouth
Damas
Busra
Cities
Study areas
Mediterranean sea
Agronomic potential
A
B
C
D
E
water
km
0
25
50
100
Coordinate System : UTM37N (WGS84)



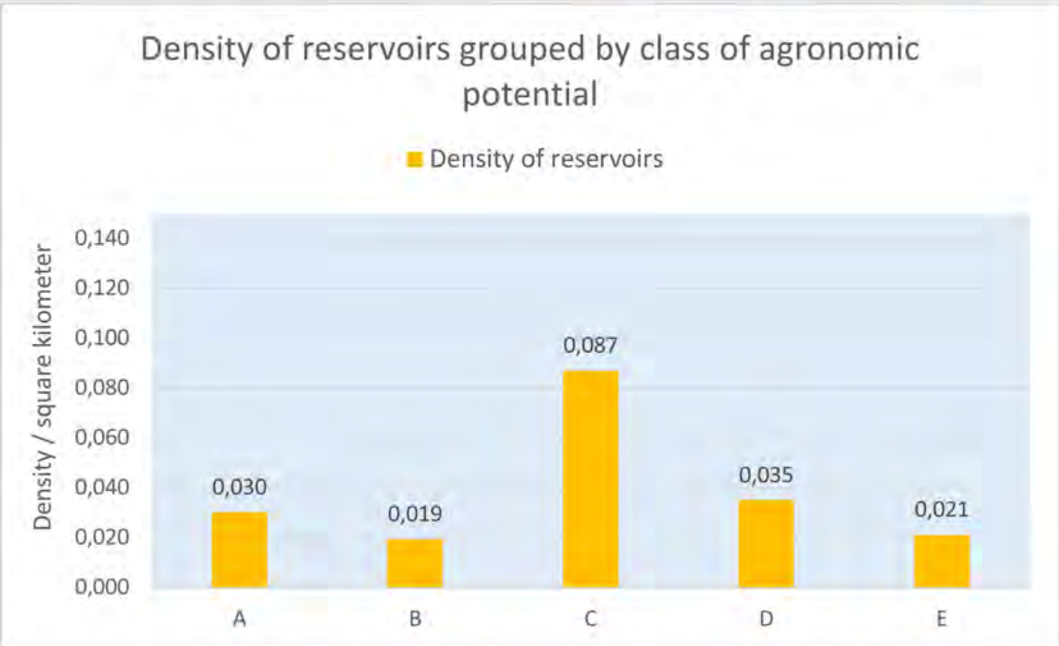
Arid Margins
Leja
Homs
N
10 km
cistern
well
tank
channel / qanats
Agronomic potential
A
B
C
D
E
Eau



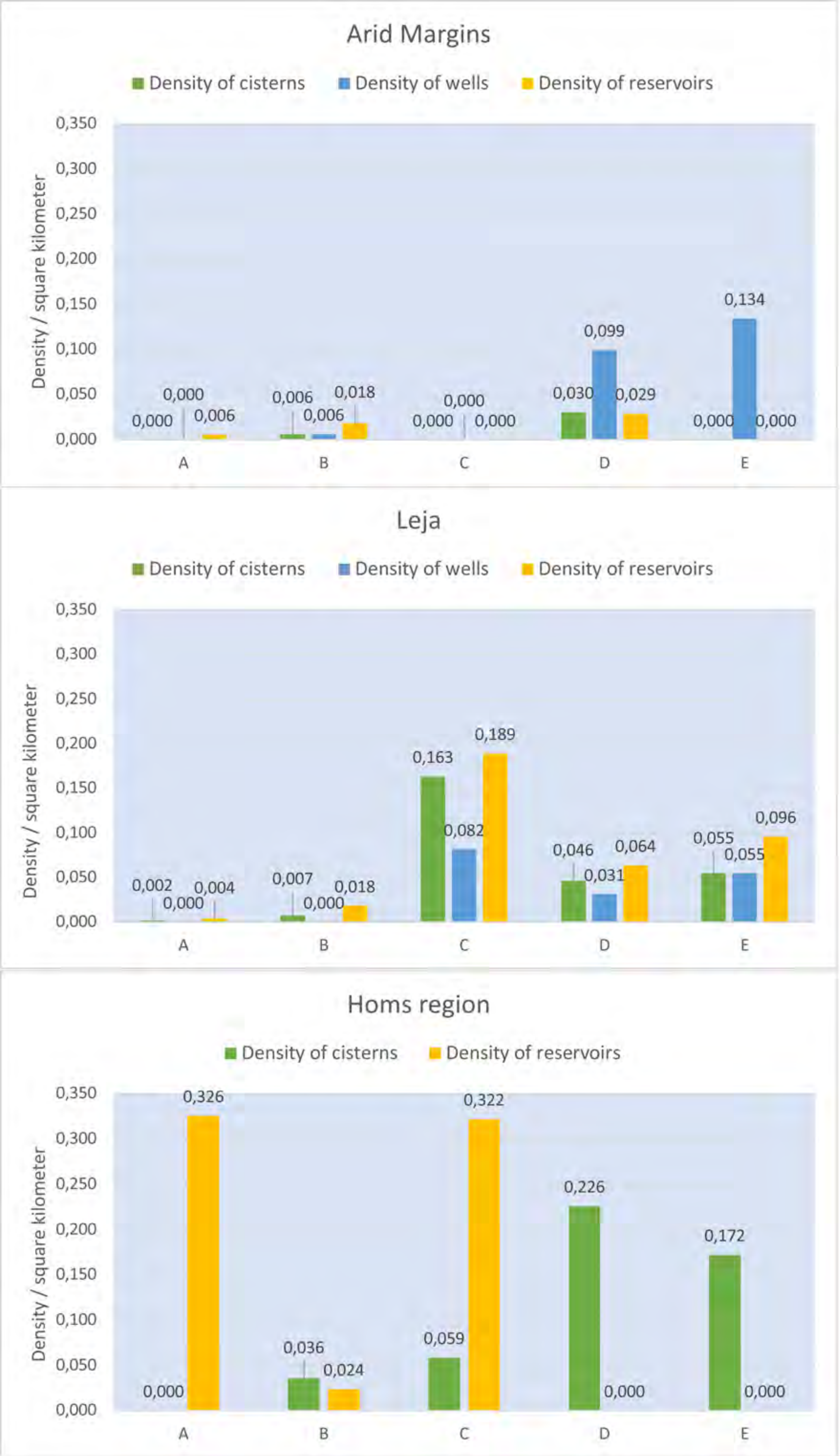
Density of cisterns
grouped by class of agronomic potential
Density of cisterns
Density / square kilometer
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
0,001
0,013
0,063
0,040
0,018
A
B
C
D
E

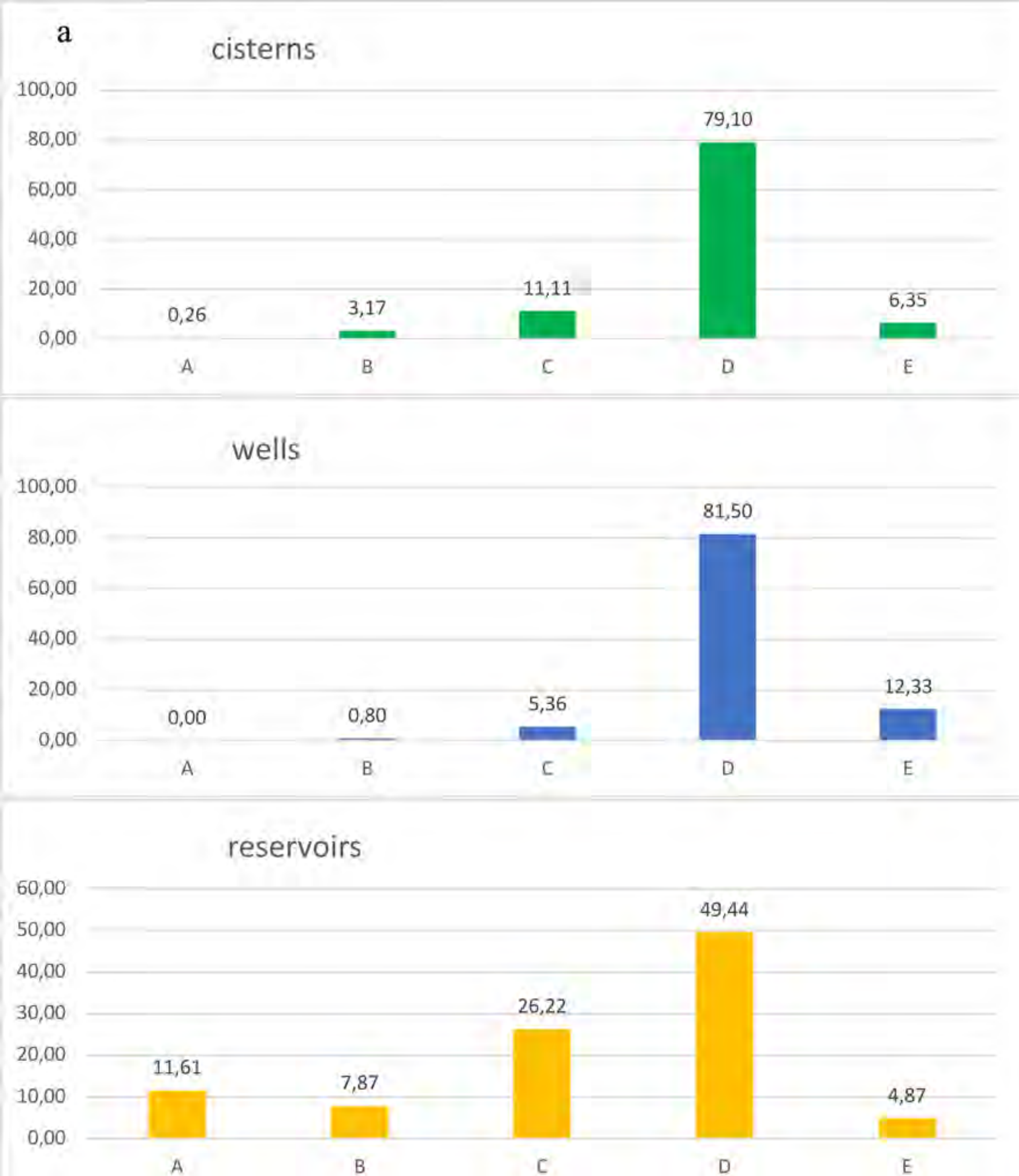


Density of wells grouped by class of agronomic potential
Density of wells
Density / square kilometer
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
0,000
0,003
0,030
0,082
0,112
A
B
C
D
E

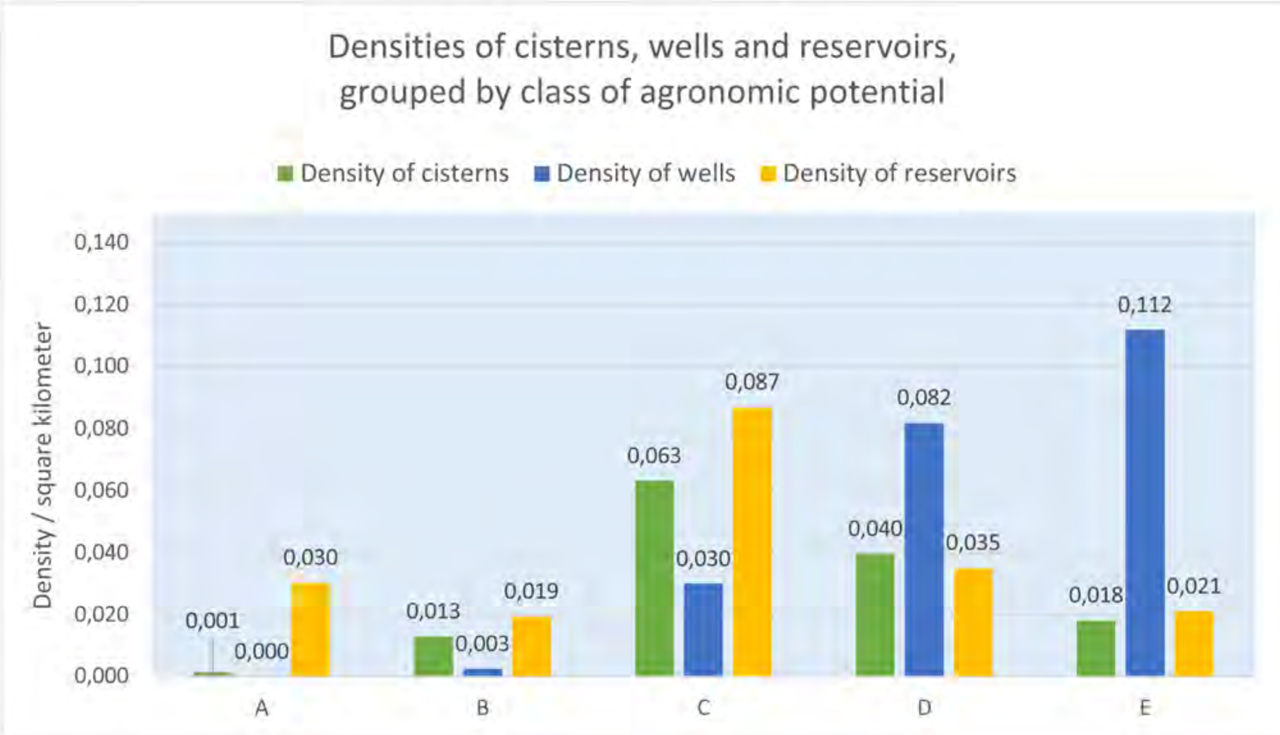


Density of reservoirs grouped by class of agronomic potential
Density of reservoirs
Density / square kilometer
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
0,030
0,019
0,087
0,035
0,021
A
B
C
D
E


Arid Margins
Density of cisterns
Density of wells
Density of reservoirs
Density / square kilometer
0,350
0,300
0,250
0,200
0,150
0,100
0,050
0,000
0,000
0,000
0,006
0,006
0,006
0,018
0,000
0,000
0,000
0,030
0,099
0,029
0,000
0,134
0,000
A
B
C
D
E
Leja
Density of cisterns
Density of wells
Density of reservoirs
Density / square kilometer
0,002
0,000
0,004
0,007
0,000
0,018
0,163
0,082
0,189
0,046
0,031
0,064
0,055
0,055
0,096
A
B
C
D
E
Homs region
Density of cisterns
Density of reservoirs
Density / square kilometer
0,000
0,326
0,036
0,024
0,059
0,322
0,226
0,000
0,172
0,000
A
B
C
D
E


a
cisterns
100,00
80,00
60,00
40,00
20,00
0,00
0,26
3,17
11,11
79,10
6,35
A
B
C
D
E
wells
100,00
80,00
60,00
40,00
20,00
0,00
0,00
0,80
5,36
81,50
12,33
A
B
C
D
E
reservoirs
60,00
50,00
40,00
30,00
20,00
10,00
0,00
11,61
7,87
26,22
49,44
4,87
A
B
C
D
E


b
100,00
80,00
60,00
40,00
20,00
0,00
0,00 0,00 1,20
0,00 0,66 7,23
0,00 0,00 0,00
93,33 88,37 92,77
6,67 10,96 0,00
A
B
C
D
E
cisterns
wells
reservoirs
c
60,00
50,00
40,00
30,00
20,00
10,00
0,00
1,27 0,00 1,90
2,53 0,00 4,76
48,10 41,30 41,90
43,04 50,00 44,76
5,06 8,70 6,67
A
B
C
D
E
cisterns
wells
reservoirs
d
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
0,00 58,33
17,14 11,11
5,71 30,56
71,43 0,00
5,71 0,00
A
B
C
D
E
cisterns
wells
reservoirs


Densities of cisterns, wells and reservoirs, grouped by class of agronomic potential
Density of cisterns
Density of wells
Density of reservoirs
Density / square kilometer
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
0,001
0,000
0,030
0,013
0,003
0,019
0,063
0,030
0,087
0,040
0,082
0,035
0,018
0,112
0,021
A
B
C
D
E